UCID- 21758

THE COST EFFECTIVENESS OF MODERNIZED U.S. STRATEGIC FORCES

Paul L. Chrzanowski

September 22, 1989

Lawrence Livermore National Laboratory

Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

THE COST EFFECTIVENESS OF MODERNIZED U.S. STRATEGIC FORCES

September 1989

Paul L. Chrzanowski
Evaluation & Planning Program
Lawrence Livermore National Laboratory
Livermore, CA 94550

Abstract

A methodology to compare the cost effectiveness of modernized U.S. strategic forces is presented and demonstrated using open literature sources for cost and performance. An important figure of merit that is used is the number of effective weapons per program dollar spent. For weapons to be effective, they must survive a first strike, be reliable, and penetrate Soviet defenses to reach the intended target. With the cost numbers gathered and assumptions used about force effectiveness, we are able to make some comparisons among possible future force options. Perhaps the most important factor in the analysis is the alert status of U.S. forces at the time of a Soviet first strike, and the conclusions drawn must be qualified by the assumptions made about force readiness at the time of the attack.

THE COST EFFECTIVENESS OF MODERNIZED U.S. STRATEGIC FORCES

Paul L. Chrzanowski
Evaluation & Planning Program
Lawrence Livermore National Laboratory
Livermore, CA 94550

Introduction

The Strategic Modernization Program pursued during the Reagan Administration has resulted in substantial improvements to the U.S. Strategic Triad: upgrade of strategic C^3 systems together with development and deployment of Trident-I submarines, B-1B bombers, and silo-based Peacekeeper missiles. These program efforts, other substantial tactical program thrusts, and improved readiness of U.S. forces have been financed by growth in the DoD budget during the 1980s. From Fiscal Year 1979 (FY79) to FY85, the DoD Budget Authority increased from $124 B to $286 B (or about 64% in constant dollars). However, since FY85, the Budget Authority has been roughly constant, representing over an 11% decline in purchasing power through FY89. The growth of the National Debt and the passage of Gramm-Rudman-Hollings has resulted in lower expectations for defense funding.

The prospects for the early-1990s are, at best, for no or little real growth for the DoD budget -- a continuing slow decline is thought to be more likely. The budget trends have resulted in a $300 B reduction in the DoD five-year defense plan between January 1987 and January 1989 even if there is 2% annual real growth in the budget for the next two years,[1] and Congress has further reduced the FY90 DoD budget below the President's request. It is clear that difficult choices will have to be made, and because of the relative constancy of manpower and operating and maintenance costs, it can be expected that Research, Development, Testing, and Engineering (RDT&E) and procurement will suffer larger cuts than the DoD overall average. Planned completion of the Strategic Modernization

Program, including fielding of Trident-II submarines, B-2 bombers, and a more survivable ICBM force, is at risk.

Many factors must be considered in sorting out the modernization options -- which to pursue on schedule, which to delay or stretch out, and which to cancel. Detailed plans cannot be developed without careful scrutiny of the entire DoD budget, policy guidance on the contribution of particular systems to our deterrence strategy, assessment of technical risks and opportunities, and information about costs and schedules. Of the spectrum of issues to be weighed by policy makers, only cost effectiveness is examined in this paper. In particular, special consideration is not given here to the unique capabilities inherent in certain elements of the strategic Triad. These and other factors also must be taken into account.

A methodology is developed in this paper to compare system cost effectiveness and it is applied to selected strategic modernization options under consideration using information available in the open literature. The methodology is intended to provide input into the planning process. When coupled with policy guidance, it may be useful in providing top-level guidance about the more effective systems to pursue in a time of constrained budgets. Perhaps extensions of the methodology could be used to assist in decisions about more detailed system or budgetary trade-offs.

To develop and apply a cost effectiveness methodology, we first present the modernization options to be considered, combinations of these force options consistent with expected provisions of a START treaty, and the effectiveness of these forces if used in retaliation to a Soviet first strike. Our measure of merit is "effective weapons" -- weapons that survive a Soviet first strike, are reliable, and penetrate Soviet defenses. The sensitivity of the number of effective weapons to variations in system performance and threat is shown.

Our choice of the number of effective weapons as the measure of merit represents a compromise. On the one hand, effective weapons is a better figure of merit than number of deployed weapons (or payload) in that it reflects two important aspects of utility in a retaliatory strike: survivability (first strike survivability, including alert rate) and ability to reach the target (reliability and defense penetrativity). On the other hand, all effective weapons are not equally capable in meeting targeting requirements. There are differences in yield, accuracy, and promptness of weapon delivery. These issues are further discussed as we introduce the measure of merit and in Appendix A.

Three measures of system cost are then defined. The first is 20-year life-cycle cost, to include RDT&E, procurement (including military construction), and operations for 20 years (hence, a total program duration of perhaps 30 years including RDT&E). The second is 20-year marginal costs. It includes the procurement cost and 20-year operational costs of the next (program size plus one) unit deployed. Our final measure is 10-year forward costs, to include only those costs to be incurred for the next ten years. The rationale and limitations of these measures are discussed. Data are presented summarizing the costs of selected strategic system options, with details relegated to Appendices.

The number of effective weapons per billion dollars is used as a measure of cost effectiveness. In what follows, the cost effectiveness of various proposed future as well as present strategic systems are compared, some general observations are made, and specific issues related to each leg of the Triad are discussed. Finally, we present a summary and discussion of areas for additional work.

Strategic system forces and performance

For some issues, such as ICBM survivability, future strategic systems must be examined in context; other deployed systems and the threat are important considerations. In this paper, we consider future strategic force structures that might be deployed in Fiscal Year 2000, and we presume that a START agreement is in effect, the terms of which have been broadly defined by negotiations during the Reagan Administration. In short, START limits the number of strategic nuclear delivery vehicles (SNDVs) to 1600 and the number of accountable weapons to 6000, no more than 4900 of which can be ICBM or SLBM warheads. A penetrating bomber counts as one SNDV and one accountable weapon.

Several unresolved issues require assumptions: mobile missile deployments are allowed, ten cruise missiles are counted per standoff heavy bomber, modernization of Soviet heavy ICBMs is permitted (but limited to 154 SNDVs), and SLCMs are not counted. Table I illustrates three postulated U.S. strategic force structures

TABLE I: POSTULATED START-CONSTRAINED U.S. STRATEGIC FORCE STRUCTURES (FY00)

	Launchers	Weapons (Counted/Actual)
Force Structure A: A 1000-RV ICBM force		
20 Trident	480	3840/3840
93 B-52H w. CMs	93	930/1860
97 B-1B	97	97/1552
132 B-2	132	132/1584
ICBM force	≤ 800	1000/1000
TOTAL	<1600	5999/9836
Force Structure B: A 2000-RV ICBM force		
20 Trident (18 tube)	360	2880/2880
89 B-52H w. CMs	89	890/1780
97 B-1B	97	97/1552
132 B-2	132	132/1584
ICBM force	≤900	2000/2000
TOTAL	<1600	5999/9796
Force Structure C: Similar to Force B, but with no B-2 deployment		
16 Trident	384	3072/3072
83 B-52H w. CMs	83	830/1660
97 B-1B	97	97/1552
ICBM force	≤1000	2000/2000
TOTAL	<1600	5999/8284

Example ICBM deployment options

For 1000 RVs: Some possible variants include: Variant 1: 100 Rail Garrison Peacekeeper; and Variant 2: 50 Rail Garrison Peacekeeper and 500 SICBM.

For 2000 RVs: The above, plus 1000 Minuteman RVs in 500 silos.

consistent with START provisions. These force structures are intended to cover a spectrum of reasonable possibilities and highlight some key issues.

In brief, Force Structure A has a (reasonable) maximum number of SLBM warheads consistent with the 4900 sub-limit on ballistic missile-delivered weapons, while Force Structure B has a (reasonable) minimum number of SLBM warheads. Force Structure C is similar to Force Structure B but illustrates the impact of a decision not to deploy the B-2. In more detail, the three force structures are:

Force Structure A: A 1000-RV ICBM force. There are over 3800 SLBM warheads (20 Trident SSBNs) deployed and only 1000 ICBM warheads in this force. Two out of many possible combinations of ICBM systems are: Variant 1 -- 100 Rail Garrison Peacekeepers; and Variant 2 -- 50 Rail Garrison Peacekeepers and 500 SICBMs.

Force Structure B: A 2000-RV ICBM force. For this force structure, there is a smaller number of SLBM warheads in comparison with Force A. In Table I, the example force structure has 6 of 24 launchers in the Trident submarines disabled to maintain 20 submarines in the force; the other possibility is to deploy only 15 Tridents. For the 2000 ICBM warheads, our presumption is that 1000 RVs are based in 500 Minuteman silos and the remainder are more survivably based.

Force Structure C: Similar to Force B, but with no B-2 deployment. Force C includes no B-2 bombers and increases the number of Trident warheads in the force (16 submarines with 24 launchers) as compared to Force B. The number of ICBMs deployed is the same in Forces B and C.

For each force structure, the number of ICBM RVs could be adjusted to a slightly lower value to accommodate 96 B-52Hs with cruise missiles, rather than the numbers shown in the table. The penetrating bomber loadings presumed are those used by Warner and Ochmanek.[2]

Table II provides a summary of the performance parameters in the FY00 time frame for the forces we are considering. With one exception that is noted, the values assumed for alert rates and the combination of reliability and defense penetrativity are those used by May, Bing, and Steinbruner.[3] We also include in the table our

TABLE II: PERFORMANCE FACTOR ASSUMPTIONS

	Alert Rate gen./ungen.	Reliability & Penetrativity	Survivability of alert forces
ICBMs in silos	1.0/0.85	0.8	0.04/1.0 for PRL
Mobile ICBMs	1.0/0.75	0.8	see note below
SLBMs	0.75/0.66	0.8	1.0
Bombers (except case below)	0.95/0.33	0.72	1.0
B-1Bs without ECM upgrade	0.95/0.33	0.55	1.0

Notes

- May, et. al.[3] use 0.72 as an aggregate figure for the combination of reliability and defense penetrativity for all bomber systems. The B-1B is reported[4] to improve its defense penetrativity by 25% to 30% with an ECM upgrade. Therefore, we use 0.55 for the base case.

- To determine ICBM survivability, we assume that the Soviets are willing to devote their START-constrained heavy ICBM force to counterforce attacks (1500 RVs). If the U.S. has ICBM silos, they are attacked 2-on-1 (with a P_S of 0.04 if the Soviet RVs also have a reliability of 0.8 and $P_K = 1$). All alert silo-based ICBMs survive if a prompt retaliatory launch (PRL) is executed. The same P_S value is used for Rail Garrison Peacekeeper in an ungenerated posture. For attack of other alert ICBM systems, the survivability (P_S) is given by[5]

System	Number of attackers 500	750	1000	1500
SICBM/HML/SW basing *or* Peacekeeper/Rail Garrison	0.93	0.89	0.86	0.79
SICBM/HML/MM area	0.88	0.82	0.76	0.65

data for the first strike survivability of alert forces. These performance factors are used to determine the number of "effective" weapons in a second strike by U.S. forces. Weapons must survive a first strike, be reliable, and penetrate Soviet defenses to be effective.

Our figure of merit treats all effective weapons as being equivalent in value. For some target types, the yield and/or accuracy of the weapon are important and should be factored into a measurement of weapon worth. Also, for some targets promptness of weapon delivery is critical. For these reasons, it is important to augment our studies (based on effective weapons as a measure of merit) with strategic exchange analyses using a realistic target base, targeting priorities, and weapon yields and accuracies to determine overall effectiveness. Some issues and complications associated with the use of exchange analyses are discussed in Appendix A.

Figure 1 and Figure 2 illustrate the number of effective weapons for the START constrained force structures we postulated. For the first graph Variant 1 is considered and Variant 2 results are shown in Figure 2. In both cases, the number of effective warheads for each leg of the strategic Triad is displayed. Three factors tend to dominate these results:

- The most important factor is the presumption about the alert status of forces -- whether forces are generated or ungenerated. In the ungenerated case, only 33% of the bomber forces are on alert and survive a Soviet first strike, and we presume that the rail-mobile Peacekeepers are not deployed from their garrisons. The overall difference is about a factor of two: 2500 to 3000 effective weapons in the ungenerated case and 5000 to 6000 in the generated case.

- Another important factor is whether or not the B-2 is deployed (Force C compared to Force A or B), particularly in the generated force cases. As can be seen from Table I, the U.S. has nearly 1600 fewer weapons in a strategic force without the B-2 because of the START counting rule for penetrating heavy bombers.

- The final major factor that affects results is the assumption whether or not the U.S. executes a prompt retaliatory launch (PRL) with its silo-based ICBMs (for Force B or C). For the purpose of analysis, we do not assume that the system can execute a PRL because of the possibility of a short time of flight SLBM threat to Rail Garrison Peacekeeper.[6]

Figure 1: Effective Weapons for Variant 1

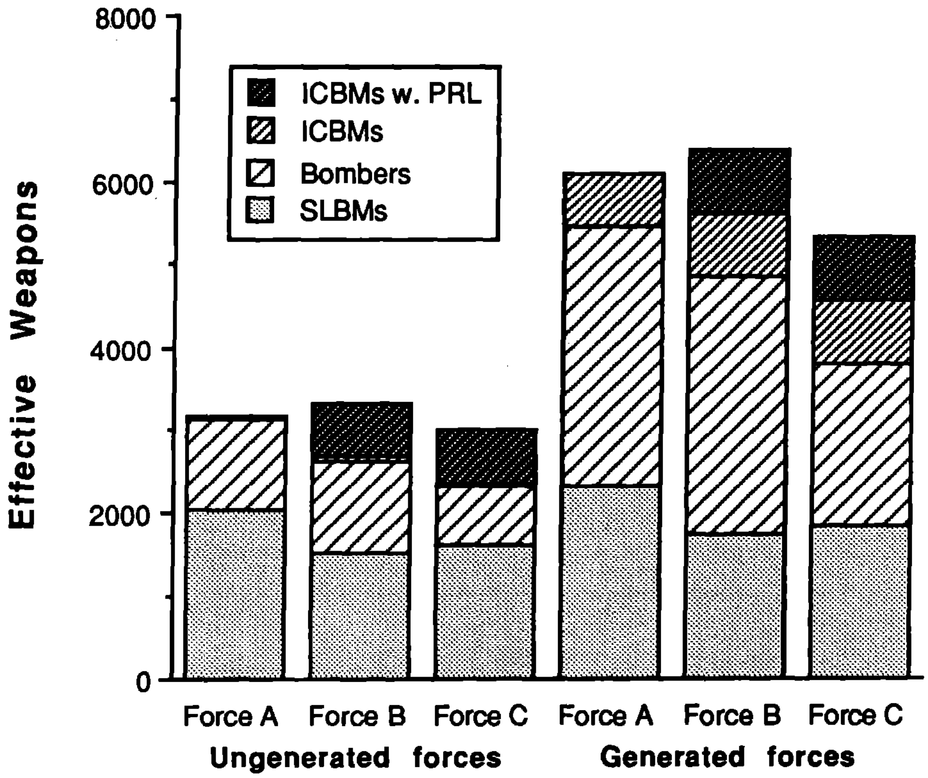

Figure 1: Effective weapons for Variant 1. For Variant 1 there are 100 Rail Garrison Peacekeeper missiles deployed. Also, it is presumed that the B-1B ECM suite has not been upgraded. The graph depicts the number of effective weapons for each leg of the strategic Triad. For the ungenerated force cases, Rail Garrison Peacekeepers are assumed to be in garrison. Results are shown for both the rideout and prompt retaliatory launch (PRL) case for Minuteman in silos. Force A has 1000 ICBM RVs, Force B has 2000 ICBM RVs, and Force C is similar to Force B but includes no B-2 bombers.

Figure 2: Effective Weapons for Variant 2

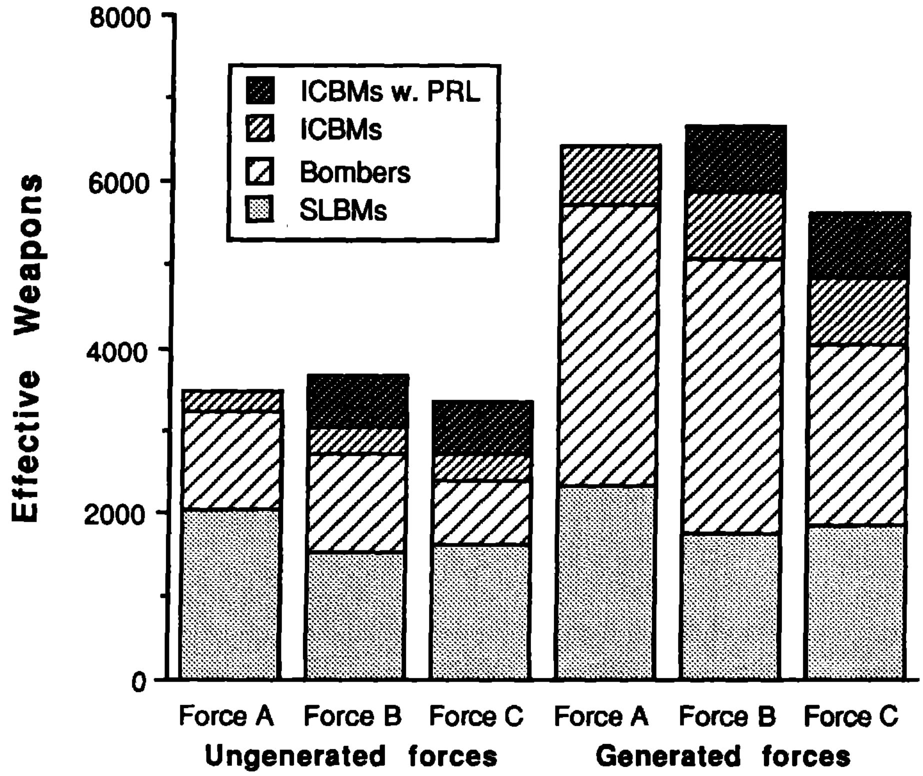

Figure 2: Effective weapons for Variant 2. For Variant 2 there are 50 Rail Garrison Peacekeeper missiles and 500 SICBMs deployed in Southwest basing. In contrast to Variant 1, the B-1B ECM suite is presumed to have been upgraded for Variant 2. The graph depicts the number of effective weapons for each leg of the strategic Triad. For the ungenerated force cases, Rail Garrison Peacekeepers are assumed to be in garrison. Results are shown for both the rideout and prompt retaliatory launch (PRL) case for Minuteman in silos. Force A has 1000 ICBM RVs, Force B has 2000 ICBM RVs, and Force C is similar to Force B but includes no B-2 bombers.

Figures 1 and 2 indicate that U.S. retaliatory capability is not very different among the force options presented. Forces A, B, and C (in either variant) have many elements in common even though they have been constructed to span a wide range of possible choices for modernization. Two factors must be considered in making choices about future forces: cost (discussed in the following section) and the resilience of forces to changes in threat (and/or other possible sources of degradation to performance). Hedging the performance of U.S. retaliatory capability against unexpected failures and possible threats is one of the factors that motivates the force diversity that currently exists in the strategic Triad.

Future changes in the threat could include: improved Soviet anti-submarine warfare (ASW) capability, Soviet breakout of the Anti-Ballistic Missile (ABM) Treaty, Soviet breakout of or cheating with respect to START limitations on offensive forces, improved Soviet air defenses, and/or a short time-of-flight threat to U.S. strategic forces that depend on tactical warning for survival. Figures 3 and 4 provide two examples of the impact of greater-than-expected Soviet threats to U.S. retaliatory capability. Figure 3 shows the sensitivity of the number of effective weapons to our threat variations for Forces A, B, and C, Variant 2 with ungenerated forces and no PRL. Figure 4 focuses on Variant 2 of Force B and depicts the number of effective weapons for each leg of the Triad for variations in threat and assumed force readiness.

From these figures, one notes that effective Soviet ASW or ballistic missile defense has a much larger impact on U.S. retaliatory capability than Soviet violation of START limits on ballistic missile deployments, and the magnitude of the impact of reduced bomber performance depends on the alert status. However, the example threat excursions considered in Figures 3 and 4 vary in their plausibility. In general, a decision maker must weigh estimations of threat plausibility against the consequences to judge how best to hedge against possible degradations in system performance.

Strategic systems costs

Three measures of strategic system costs are considered in this paper. Each, in isolation, is limited in its ability to convey the necessary information to a decision maker, but, together, they

Figure 3:
Effective Weapons for Variant 2, Ungenerated

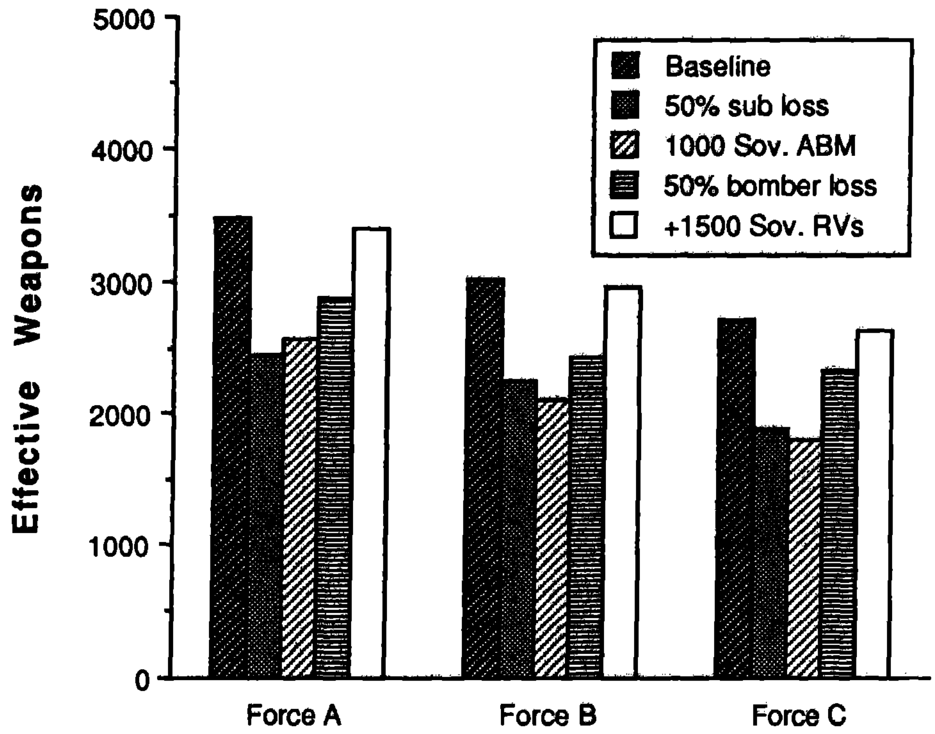

Figure 3: Effective weapons for Variant 2, ungenerated forces case with no PRL. The graph shows the number of effective weapons for the baseline case (Variant 2, ungenerated in Figure 2 with no PRL) and several variations in threat: effective Soviet ASW with 50% losses in the Trident force at sea, deployment of 1000 Soviet ABM interceptors (90% effective), 50% loss of U.S. bombers and cruise missiles (due to improved Soviet air defenses or a short time-of-flight threat to bomber bases), and Soviet deployment of 1500 RVs above the START limits. Force A has 1000 ICBM RVs, Force B has 2000 ICBM RVs, and Force C is similar to Force B but includes no B-2 bombers.

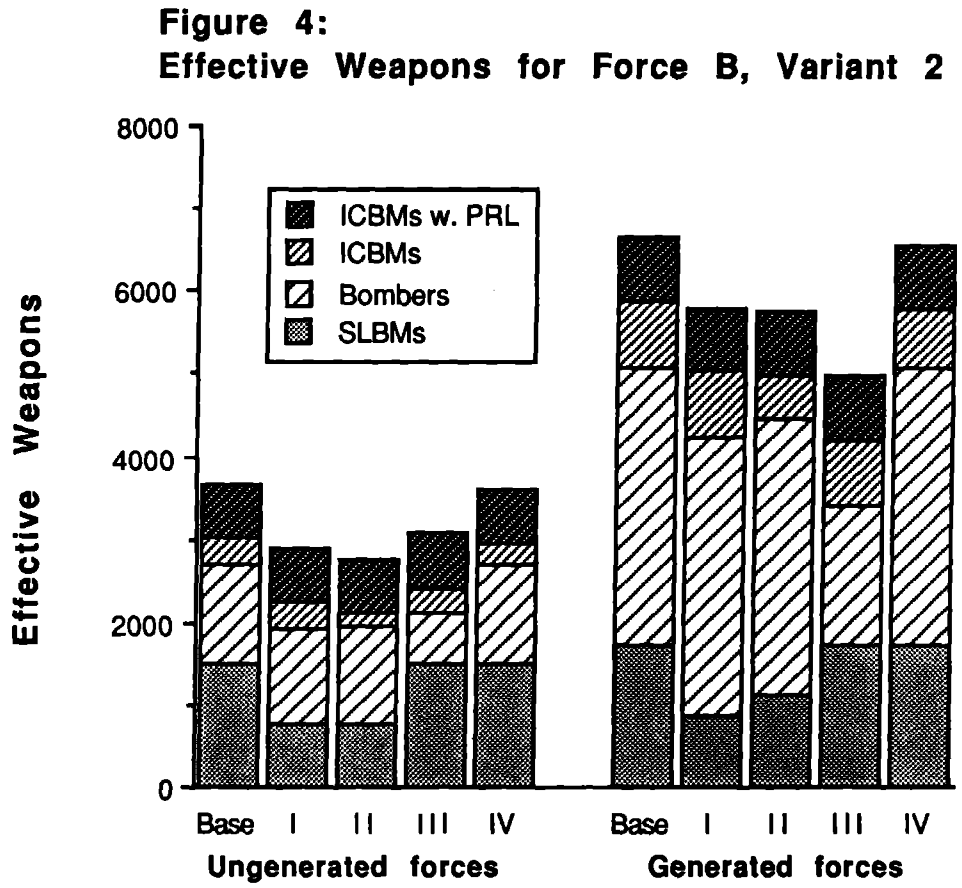

Figure 4: Effective weapons for Force B (with 2000 ICBM RVs), Variant 2. The graph shows the number of effective weapons for the baseline case (labeled "Base") and several variations in threat: "I" -- effective Soviet ASW with 50% losses in the Trident force at sea, "II" -- deployment of 1000 Soviet ABM interceptors (90% effective), "III" -- 50% loss of U.S. bombers and cruise missiles (due to improved Soviet air defenses or a short time-of-flight threat to bomber bases), and "IV" -- Soviet deployment of 1500 RVs above the START limits. For threat variation "II" (ABM deployment), the reduction in the number of effective ICBMs and SLBMs could be apportioned differently than the results shown above (but the total is constant).

provide a rather balanced perspective of system costs. The three measures, and their merits and demerits, are:

- *20-Year Life-cycle Costs*. 20-year life-cycle costs include RDT&E, procurement (including military construction), and operational costs for a (presumed) 20-year lifetime. Obviously, this cost measure provides a useful characterization of the whole program and puts it in perspective with other programs at different stages in their history. For example, 20-year life-cycle costs is an interesting measure for comparison of the B-2 with earlier bomber programs. However, these costs are not necessarily relevant for near-term budget decisions for programs already underway. A high 20-year life-cycle cost may be a consequence of money that has already been invested. Thus, this measure is generally most useful early in the program to help decisions whether to proceed or not.

- *20-Year Marginal Costs*. This measure characterizes the cost effectiveness of additional units of equipment that could be procured (beyond the planned program). Our 20-year marginal costs include procurement and 20 years of operation. It is most useful in consideration of systems for which RDT&E is essentially completed, and this cost figure can be used to address the issue of deviating from program plans by either extending or curtailing production. For systems which have long since completed production (e.g., the B-52H or Minuteman), the measure serves only as a benchmark because additional procurement is not feasible.

- *10-Year Forward Costs*. Sunk program costs are neglected in 10-year forward costs. Only the RDT&E, procurement, and operational costs (appropriated funds) for the next 10 years are included. The ten-year period is comparable to that for the acquisition process but short compared the overall life cycle of a system. Near-term budget constraints are a major concern which 10-year forward costs address, so it is useful for budgeteers. On the other hand, the measure tends to "reward" the stretching-out of programs and "discredit" RDT&E investments for future capability (beyond the 10-year time frame). For new systems, details about the rate of procurement are important for 10-year forward costs.

We have attempted to determine these three costs for many of the strategic weapon systems under consideration as part of the modernization program. Although much of the data is not from "official" government sources and not all information is the most current, we expect that the accuracy of these costs is within the bounds of uncertainty of future program costs. Table III provides the cost information, and Appendices B through E document the sources and our assumptions. These data are used in the next section to examine cost effectiveness.

Strategic system cost effectiveness

Our measure of cost effectiveness is the number of effective weapons per billion dollars (FY90) cost. To compute cost effectiveness, we use the data presented in Table II pertaining to force effectiveness and cost information from Table III. The year FY00 has been selected for our assessment of cost effectiveness. A more thorough examination of issues might be based on an integration (average) of the effectiveness over the 10-year or 20-year period considered for the cost measure.

Figures 5, 6, and 7 display the cost effectiveness of selected ICBM and SLBM options. Excursions and additional cases are discussed in the next section. For the ICBM systems, the threat is taken to be 2-on-1 targeting of silos and 1500 RVs against each of the mobile systems considered. This represents a possible worst case threat and, as discussed in a prior section, the actual threat requires specification of the total force mix (what other ICBM systems are deployed).

First, consider the 20 Trident data in Figures 5, 6, and 7. Because the system is deemed to be survivable at sea and there is little variation in the alert (at sea) rate as a function of the force generation level, there is not much difference between the generated and ungenerated forces results. The 20-year life-cycle cost effectiveness is about 20 effective weapons/$B. This figure serves as a useful benchmark for comparison of other programs. The 20-year marginal cost effectiveness is about 50% higher, which is a reflection of the fact that RDT&E, military construction, and production of missiles for testing comprise about one-third of the total program cost. The 10-year forward cost effectiveness is even higher -- about 50 effective weapons/$B. This higher cost effectiveness occurs because about half the total program investments have been made and the operating costs are lower than those for the other measures.

TABLE III: STRATEGIC SYSTEM COSTS (IN FY90 $B)

STRATEGIC SYSTEM	COSTS (FY90 $B) 20-year life-cycle	 20-year marginal*	 10-year forward
Submarines			
20 Trident	104	3.5	43
20 Trident (18 tubes)	101	3.3	39
16 Trident	90	3.5	30
Bombers			
96 B-52H with CMs	42	0.42	12
97 B-1B	56	0.40	17
97 B-1B with ECM upgrade	57	0.41	19
132 B-2	84	0.44	46
66 B-2	55	---	26
ICBMs			
1000 Minuteman in silos	34	0.93	5.8
500 Minuteman in silos	25	---	3.3
50 Peacekeeper in silos	21	0.77	5.0
50 Peacekeeper/rail garrison	32	---	12
50 silo + 50 RG Peacekeeper	34	---	15
100 Peacekeeper/rail garrison	43	2.30	19
500 SICBM/HML -- SW basing	38	---	23
500 SICBM/HML -- MM area	35	---	20
250 2-RV SICBM/HML -- SW	31	---	17

*Marginal costs are: per submarine, per bomber, or per 100 warheads for ICBMs. We have not developed the marginal costs for all systems considered.

Figure 5: Life-cycle Cost Effectiveness for Selected Missile Options

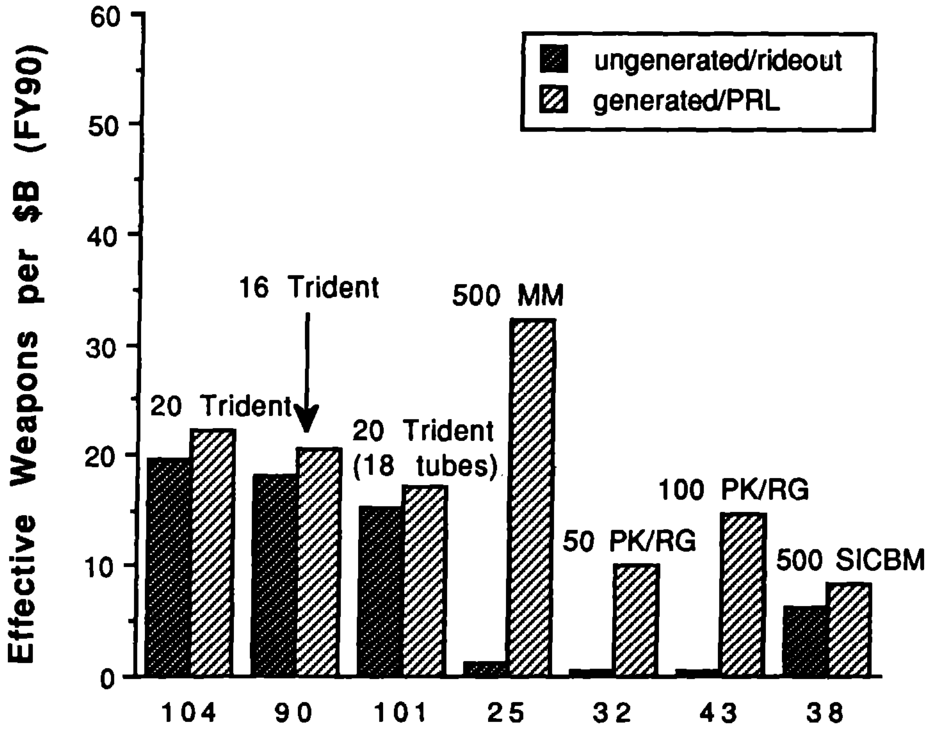

Figure 5: 20-year life-cycle cost effectiveness for selected missile options. Results for seven missile options are shown: a 20 SSBN Trident force (20 Trident), a 16 SSBN Trident force (16 Trident), a 20 SSBN Trident force with 18 launchers each (20 Trident (18 tubes)), 500 Minuteman ICBMs in silos with a total of 1000 RVs (500 MM), 50 Rail Garrison Peacekeeper (50 PK/RG), 100 Rail Garrison Peacekeeper (100 PK/RG), and 500 SICBM on HMLs with Southwest basing (500 SICBM). The threat to each non-silo-based ICBM system is taken to be 1500 Soviet RVs. The 20-year life-cycle costs are shown at the bottom of the graph. The darker bars depict cost effectiveness for ungenerated forces (in port for Trident, rideout for silo-based ICBMs, and in garrison for RG Peacekeeper). The lighter bars characterize cost effectiveness for generated forces. The number of weapons in the seven cases are, respectively: 3840, 2880, 2880, 1000, 500, 1000, and 500.

Figure 6: Marginal Cost Effectiveness for Selected Missile Options

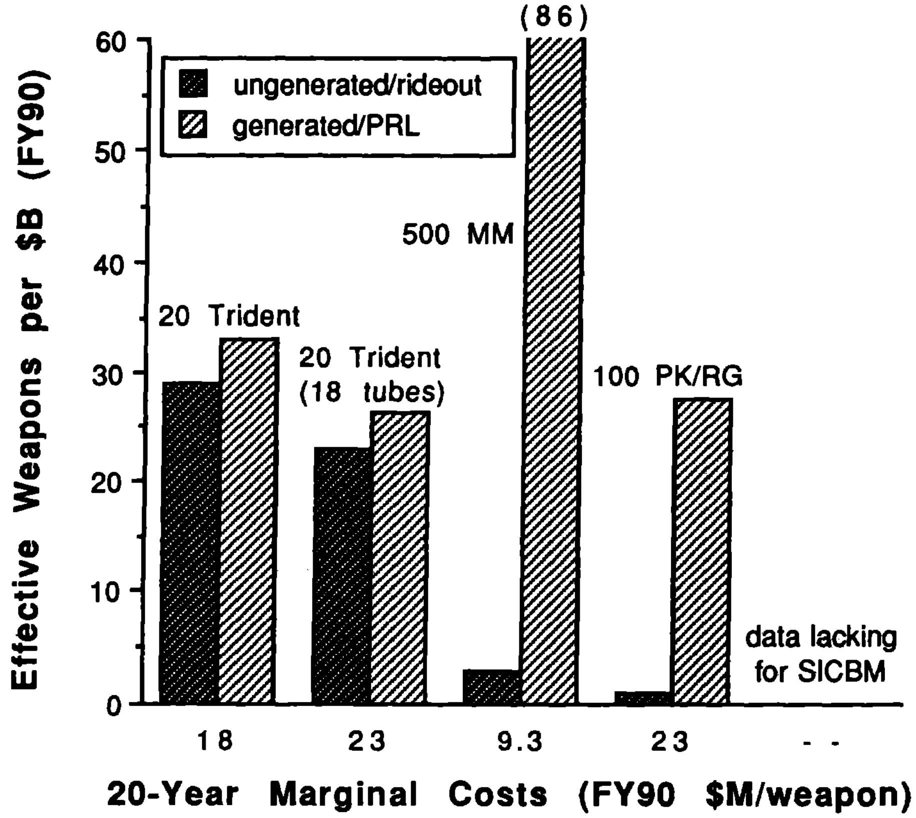

Figure 6: 20-year marginal cost effectiveness for selected missile options. Results are shown for four of the six missile options considered in Figure 5: a 20 (or 16) SSBN Trident force (20 Trident), a 20 SSBN Trident force with 18 launchers each (20 Trident (18 tubes)), 500 Minuteman ICBMs in silos with a total of 1000 RVs (500 MM), and 100 (or 50) Rail Garrison Peacekeeper (100 PK/RG). Insufficient data were gathered to estimate reliably the SICBM marginal costs. The threat to each non-silo-based ICBM system is taken to be 1500 Soviet RVs. The 20-year marginal costs are shown at the bottom of the graph. The darker bars depict cost effectiveness for ungenerated forces (in port for Trident, rideout for silo-based ICBMs, and in garrison for RG Peacekeeper). The lighter bars characterize cost effectiveness for generated forces.

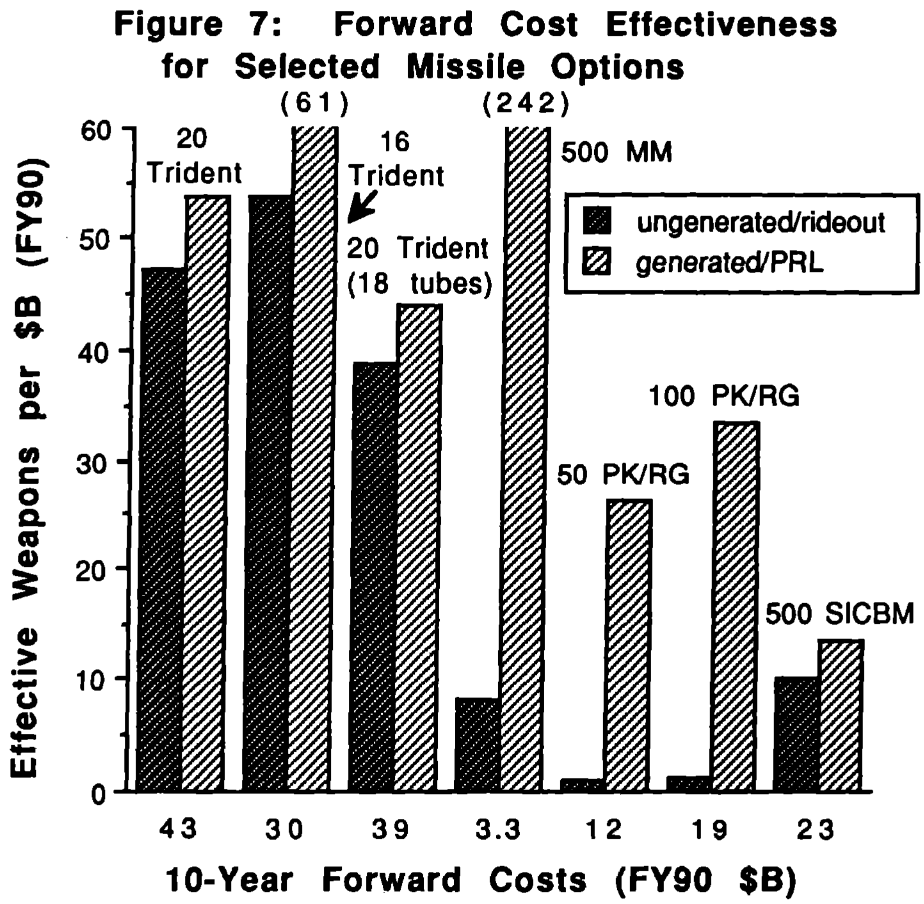

Figure 7: 10-year forward cost effectiveness for selected missile options. Results for seven missile options are shown: a 20 SSBN Trident force (20 Trident), a 16 SSBN Trident force (16 Trident), a 20 SSBN Trident force with 18 launchers each (20 Trident (18 tubes)), 500 Minuteman ICBMs in silos with a total of 1000 RVs (500 MM), 50 Rail Garrison Peacekeeper (50 PK/RG), 100 Rail Garrison Peacekeeper (100 PK/RG), and 500 SICBM on HMLs with Southwest basing (500 SICBM). The threat to each non-silo-based ICBM system is taken to be 1500 Soviet RVs. The 10-year forward costs are shown at the bottom of the graph. The darker bars depict cost effectiveness for ungenerated forces (in port for Trident, rideout for silo-based ICBMs, and in garrison for RG Peacekeeper). The lighter bars characterize cost effectiveness for generated forces. The number of weapons in the seven cases are, respectively: 3840, 2880, 2880, 1000, 500, 1000, and 500.

In general, although the forward costs are critical for budget considerations, we find that the 10-year forward cost effectiveness is the most erratic of our figures of merit because of the strong sensitivity of results to the current development phase of the program. Most of our subsequent discussion focuses on the other two cost effectiveness measures.

For ICBMs in silos, the cost effectiveness depends critically on the scenario: PRL or rideout of a Soviet attack. In the former case, the figures of merit are much higher than for other systems and in the latter case much lower. Forward cost effectiveness of Minuteman in silos with PRL is particularly high because operational costs are low, as are the costs to be incurred for modernization of Minuteman.

The 20-year life-cycle cost effectiveness of systems using the Peacekeeper missile tend to be lower than that for Trident. An important contributing factor is the small number of missiles deployed (50 to 100), which must amortize the development costs of the program and the procurement of missiles for the flight test program. Without these costs, which is the case for the 20-year marginal cost measure, Rail Garrison Peacekeeper in a generated posture is competitive with Trident. More generally, the issue with Rail Garrison Peacekeeper is not the cost effectiveness of a generated (deployed) force, but the poor performance of the system in the (unlikely) event of no strategic warning or in the event of a failure to act on strategic warning.

For SICBM (HML with Southwest basing), the 20-year life-cycle cost effectiveness is about a factor of two lower than that for Trident. Expense is and has been a major issue with the program. The system does have the virtue that there is little difference in performance between the generated and ungenerated cases.

Figures 8, 9, and 10 present results for selected bomber systems. Several features of these graphs are particularly noteworthy:

- The most critical factor is the alert status of the bombers. There is a factor of three difference between the cost effectiveness of a generated force and an ungenerated force. In the generated case with our assumptions about bomber penetrativity, the 20-year life-cycle cost effectiveness of bombers is competitive (10 to 30 effective weapons/$B) with Trident and so are the marginal costs.

Figure 8: Life-cycle Cost Effectiveness for Selected Bomber Options

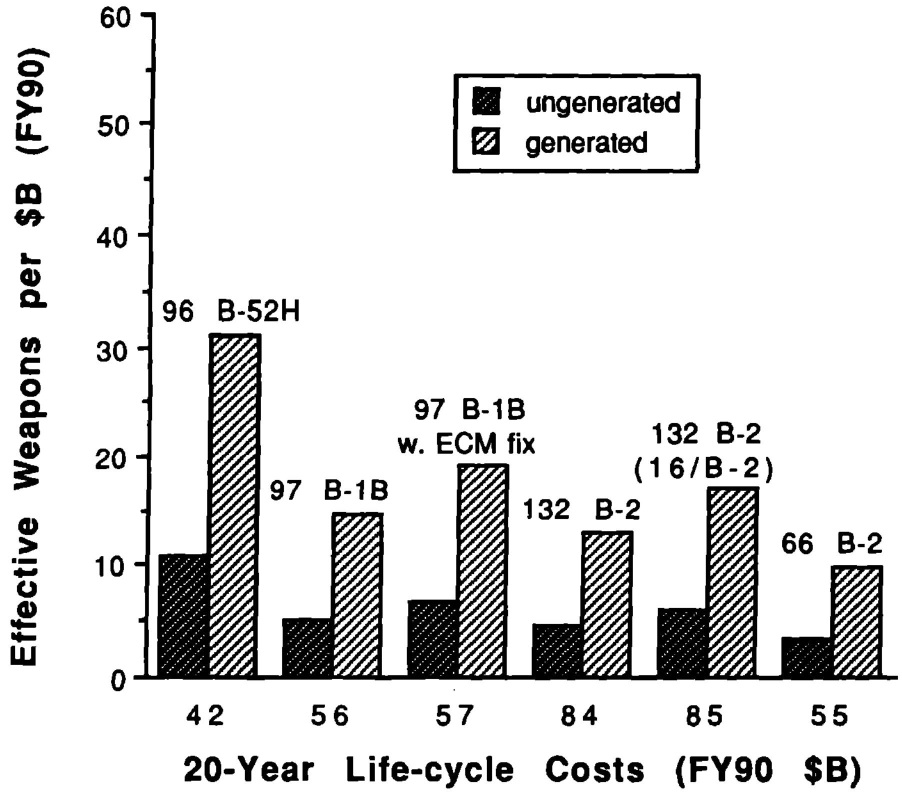

Figure 8: 20-year life-cycle cost effectiveness for selected bomber options. Results for six bomber options are shown: 96 B-52H loaded with 20 ALCMs/ACMs (96 B-52H), 97 B-1B loaded with 16 weapons (97 B-1B), 97 B-1B with an upgrade of the ECM suite and loaded with 16 weapons (97 B-1B w. ECM fix), 132 B-2 loaded with 12 weapons (132 B-2), 132 B-2 loaded with 16 weapons (132 B-2 (16/B-2)), and 66 B-2 loaded with 12 weapons. The 20-year life-cycle costs are shown at the bottom of the graph. The darker bars depict cost effectiveness for ungenerated forces and the lighter bars characterize cost effectiveness for generated forces. The number of weapons for these six options are, respectively: 1920, 1552, 1552, 1584, 2112, and 776.

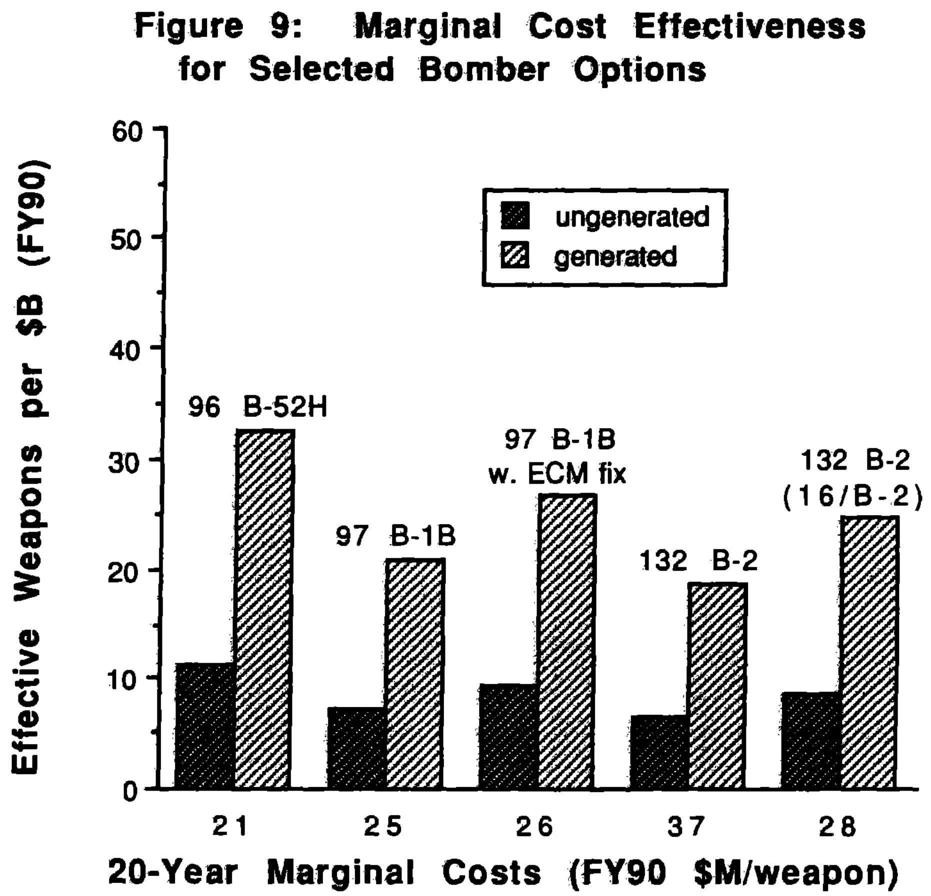

Figure 9: 20-year marginal cost effectiveness for selected bomber options. Results for five bomber options are shown: 96 B-52H loaded with 20 ALCMs/ACMs (96 B-52H), 97 B-1B loaded with 16 weapons (97 B-1B), 97 B-1B with an upgrade of the ECM suite and loaded with 16 weapons (97 B-1B w. ECM fix), 132 (or 66) B-2 loaded with 12 weapons (132 B-2), and 132 B-2 loaded with 16 weapons (132 B-2 (16/B-2)). The 20-year marginal costs are shown at the bottom of the graph. The darker bars depict cost effectiveness for ungenerated forces and the lighter bars characterize cost effectiveness for generated forces. The number of weapons for these five options are, respectively: 1920, 1552, 1552, 1584, and 2112.

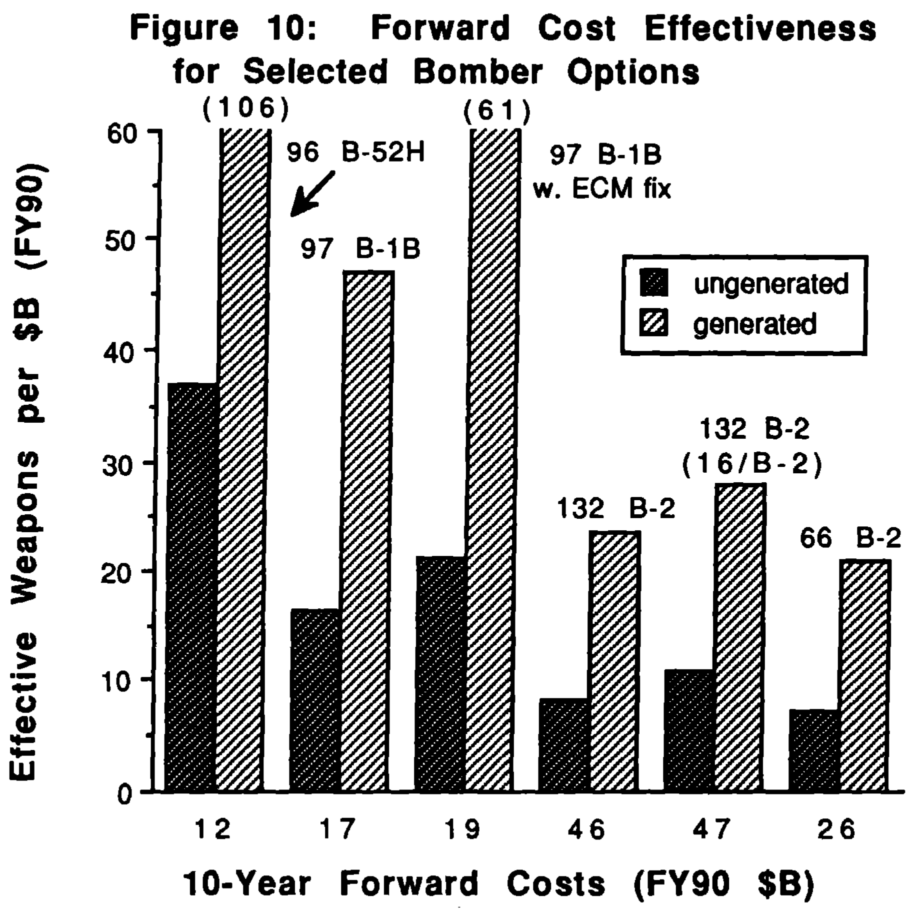

Figure 10: 10-year forward cost effectiveness for selected bomber options. Results for six bomber options are shown: 96 B-52H loaded with 20 ALCMs/ACMs (96 B-52H), 97 B-1B loaded with 16 weapons (97 B-1B), 97 B-1B with an upgrade of the ECM suite and loaded with 16 weapons (97 B-1B w. ECM fix), 132 B-2 loaded with 12 weapons (132 B-2), 132 B-2 loaded with 16 weapons (132 B-2 (16/B-2)), and 66 B-2 loaded with 12 weapons. The 10-year forward costs are shown at the bottom of the graph. The darker bars depict cost effectiveness for ungenerated forces and the lighter bars characterize cost effectiveness for generated forces. The number of weapons for these six options are, respectively: 1920, 1552, 1552, 1584, 2112, and 776.

- An important issue regarding the B-2 bomber is the weapon loading. In accordance with analyses by Warner and Ochmanek[2] and Hildreth, et. al.,[7] we presume a typical loading of 12 weapons per B-2. Other sources[8] characterize the payload as being "roughly equivalent to that of the B-1B," which we take to be 16 weapons.[9] If loaded with 16 weapons and if the bomber can penetrate as well as we presume, a generated B-2 force is nearly as cost effective as Trident.

- The very high 10-year forward cost effectiveness of the B-52H and B-1B forces are due to the fact that major program investments have already been made.

In short, 20-year life-cycle and 20-year marginal cost effectiveness appear to be more useful figure of merits than 10-year forward cost effectiveness although the forward costs are important for decision makers. A useful benchmark for comparison of programs is the 20 Trident case. We highlight some major program issues for each leg of the Triad in more detail in the next section.

Some strategic system program issues

The SLBM force: How many Tridents?

As can be noted from Figures 5 through 10, 20 Trident SSBNs constitute a comparatively very cost effective force. If future strategic forces are constrained by START, two principal issues to be faced are the number of warheads to be devoted to the SLBM leg of the Triad and the configuration of the submarines to insure that there are an adequate number of SSBNs at sea at all times.

Figures 1 and 2 illustrate that Force A (with a large Trident fleet) results in more effective weapons than Force B (with a smaller Trident fleet) except in scenarios where the silo-based ICBMs successfully execute a PRL. In addition, Figure 11 illustrates that Force A is more cost effective (using 20-year life-cycle costs) than Force B, even in scenarios where silo-based ICBMs execute a PRL. One major factor lowers the cost effectiveness of Force B: if the Trident force is reconfigured to SSBNs with 18 launchers, the cost effectiveness is reduced from about 21 effective weapons/$B to about 16 effective weapons/$B (see Figure 5). The alternative is to

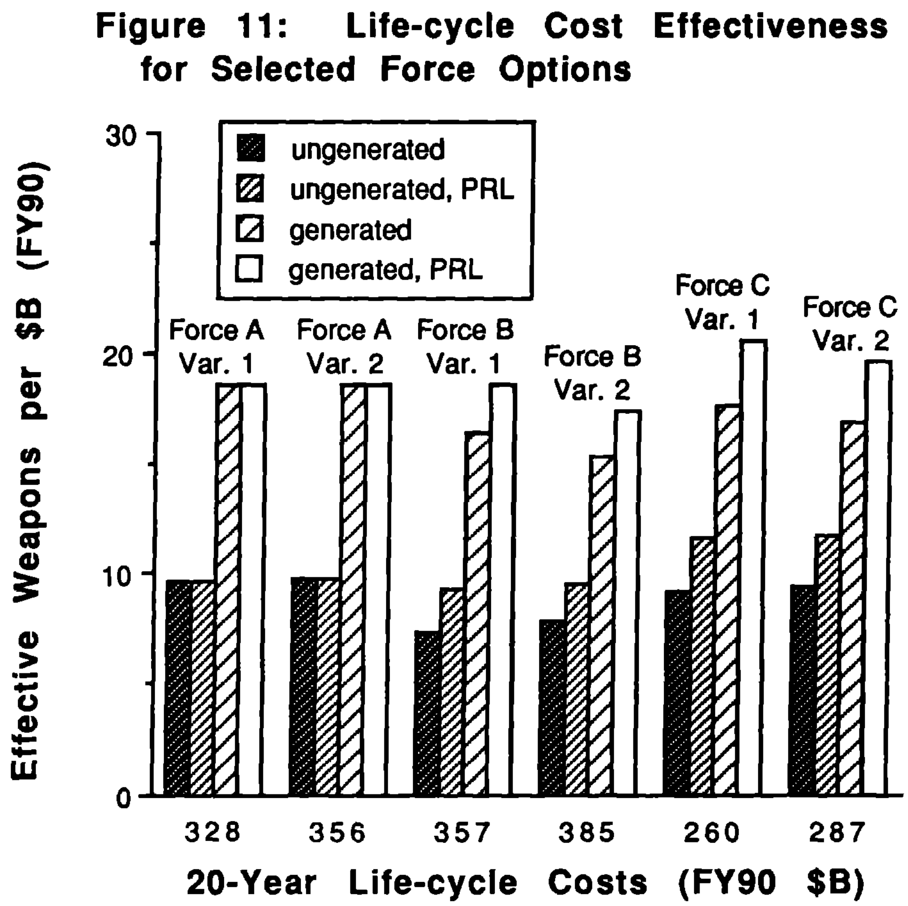

Figure 11: 20-year life-cycle cost effectiveness for selected force options. The 20-year life-cycle cost effectiveness of the force structures defined by Table II is shown for four scenarios: ungenerated forces, ungenerated forces with PRL of silo-based ICBMs, generated forces, and generated forces with PRL of silo-based ICBMs. The 20-year life-cycle costs are shown at the bottom of the graph.

reduce the size of the fleet, which exacerbates some concerns[10] about "too many eggs in too few baskets" and reduces cost effectiveness. For a 2000-RV ICBM START-constrained force, cost effectiveness tends to be reduced. One does not take advantage of the high marginal cost effectiveness of building additional Tridents (say, from 15 SSBNs to 20 SSBNs). Also, if the SLBM warheads are replaced with survivable ICBM RVs, a (perhaps large) RDT&E investment must be made for the ICBM program to procure what may be a small number of deployed RVs.

While Force A is more cost effective than Force B, Force A places much more reliance on submarine survivability than Force B and could be considered to be unbalanced for that reason. A possible hedge to concerns about submarine survivability would be Force B with ICBMs that are survivable even in the absence of warning. However, should the U.S. ICBM force be larger than about 1000 weapons under START, the number of Trident submarines must be reduced to below 20, warheads must be off-loaded from missiles, or fewer launchers must be present on each SSBN. As noted above, any of these options will reduce the overall cost effectiveness of U.S. forces in retaliation, and the off-loading options raise what might be complicated treaty verification issues.

The ICBM force: Whither ICBMs?

There are ICBM deployment options other than those depicted in Figures 5, 6, and 7 for which we have developed cost data, and their 20-year life-cycle cost effectiveness are shown in Figure 12. Two comparisons are particularly interesting:

- The cost effectiveness of silo-based Peacekeeper is not very high even in the PRL (generated) case because so few missiles are deployed and they must amortize the RDT&E expenses and missiles for the test program.

- The most cost effective SICBM/HML system is the 2 RV per missile option, and Southwest basing appears to be more cost effective than Minuteman area basing. Although more expensive, Southwest basing offers greater survivability than Minuteman area basing. (In addition, Minuteman area basing requires tactical warning for survival.) However, because the return for a Soviet attack of SICBM is low (65% to 80% survival of alert SICBM warheads in a 1500 RV attack), the Soviets may not choose to barrage SICBM

Figure 12: Life-cycle Cost Effectiveness for Additional ICBM Options

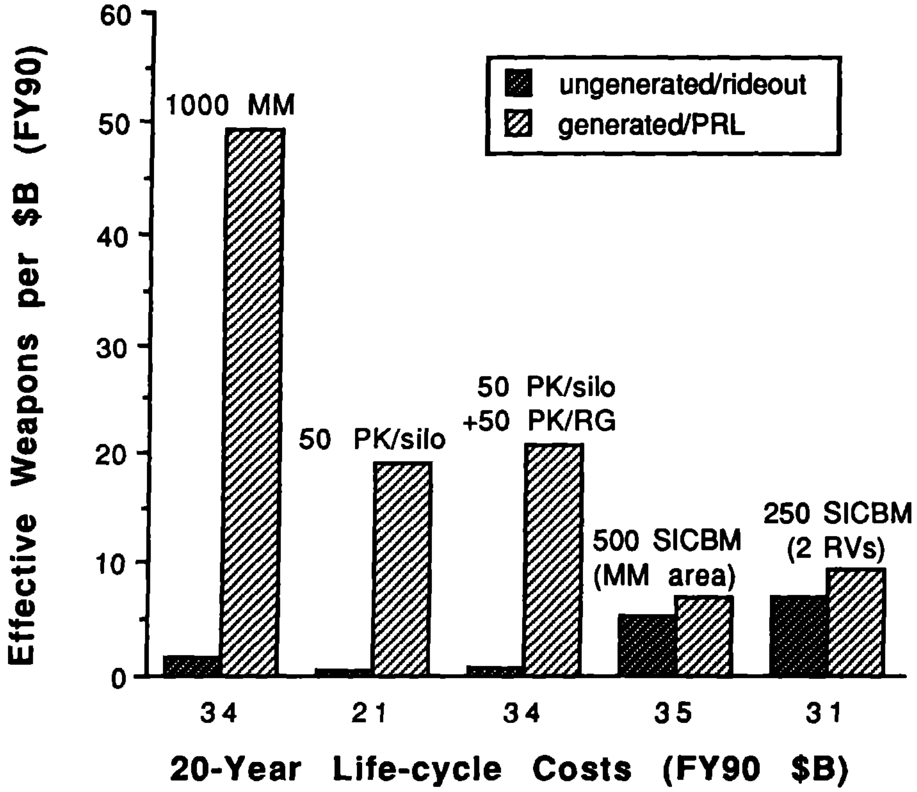

Figure 12: 20-year life-cycle cost effectiveness for additional ICBM options. Results for five other options are shown: 1000 Minuteman ICBMs in silos with a total of 2100 warheads (1000 MM), 50 Peacekeeper missiles in silos (50 PK/silo), 50 Peacekeeper missiles in silos plus 50 Rail Garrison Peacekeeper (50 PK/silo + 50 PK/RG), 500 SICBM on HMLs based near MM silos (500 SICBM (MM area)), and 250 SICBM on HMLs with 2 RVs each and Southwest basing (250 SICBM (2 RVs)). The threat to each non-silo-based system is taken to be 1500 Soviet RVs. The 20-year life-cycle costs are shown at the bottom of the graph. The darker bars depict cost effectiveness for ungenerated forces (rideout for silo-based ICBMs and in garrison for RG Peacekeeper). The lighter bars characterize cost effectiveness for generated forces.

deployment areas. In that case, Minuteman area basing is the cheaper option. More generally, the cost effectiveness of mobile missile options increases by over 25% for the case where the Soviet do not conduct a 1500-RV barrage attack (for SICBM in Minuteman areas, the increase is over 50%).

Whichever modernization options are followed, it remains the case that, in the START forces we analyze, ICBMs contribute a smaller number of effective weapons than the other legs of the Triad for almost all scenarios, including those with PRL (see Figures 1 and 2). The only exception is Force C, Variant 2 in the ungenerated case if silo-based ICBMs execute a PRL. In the cases where 1000 Minuteman RVs are in the force (Forces B and C) and they execute a PRL, ICBMs contribute up to about 30% of the number of effective weapons.

If the U.S. is to maintain a balanced Triad that is effective in retaliation to a Soviet first strike and not rely on PRL of silo-based ICBMs, ICBM modernization must result in more than 1000 RVs in survivably-based systems. With 2000 survivably-based ICBM RVs, the number of effective weapons in Figure 3 would increase by about 800, which would alleviate some of the impact of increased Soviet threats. However, the costs of such a force are twofold: survivable ICBM systems are generally expensive and not as cost effective as Trident, and if the Trident force is reduced in size to accommodate a 2000-RV ICBM force, it is not as cost effective as a larger Trident force (see Figure 5).

The bomber force: B-1B upgrade? B-2 or no B-2?

Our "selected bomber option" results shown in Figures 8, 9, and 10 suggest that bomber forces are cost effective if fully generated. In Figure 8, the performance of the B-52H (with cruise missiles) force exceeds that of the B-1B force, which, in turn, is better than the performance of the B-2 force. A similar pattern is followed by the marginal cost effectiveness (Figure 9).

These observations must be qualified by our presumptions about bomber loadings, bomber base safe escape, and ability to penetrate Soviet air defenses. With changes in these assumptions, there are variations in the performance of the bomber options relative to each other and to the other legs of the Triad. Some key considerations are:

• Bomber base safe escape: Our baseline performance parameters (Table II) are such that the combination of probability of safe base escape and penetration of Soviet air defenses is 0.9 (for weapons assumed to be 80% reliable). In effect, there is no attrition of alert bombers due to Soviet SLBM attacks of SAC airbases. Work by Speed[11] suggests that a few Soviet submarines close to U.S. coastlines can damage (in a barrage attack) a non-negligible fraction of the alert bombers in flight. The cost effectiveness of bombers is proportional to the fraction of alert aircraft able to escape. Thus, consideration of base safe escape could lower the cost effectiveness of bomber systems compared to ICBM and SLBM options. In addition, the cost effectiveness of the B-52H option could be lowered relative to the B-1B and B-2 options because SAC bases for the former tend to be located closer to U.S. coastlines and therefore attrition would be higher.[11]

• B-1B air defense penetrativity and ECM upgrades: In Table II, our estimate for the reliability and penetrativity of the B-1B in the year FY00 is 0.55 and 0.72 with an upgrade of the ECM suite, corresponding to penetrativities of 0.7 and 0.9 if weapon systems are 80% reliable (as assumed for missile systems). According to *Aerospace Daily*,[12] the B-1B with upgrades will be able to penetrate Soviet air defenses "into 'the later-90s'" while sustaining "acceptable losses" but "that capability will erode to the point of becoming ineffective in those highly defended areas." In contrast, the B-2 would be able to penetrate these same defenses "virtually unchallenged." This suggests that our estimate of B-1B relative performance and cost effectiveness may be too high. If lowered, the B-1B life-cycle and marginal cost effectiveness could be bettered by the B-2 even if the latter carries only 12 weapons. As for the ECM upgrade of the B-1B, the data in Table III suggest that upgrades would be cost effective if the air defense penetrativity improvement is only 3% ($47.9 B/$46.5 B - 1). A 30% improvement is anticipated (see Appendix C).

• Bomber loading factors: As discussed in the previous section, a key factor for the B-2 cost effectiveness is the average weapon loading. If the loading is 16 weapons, the B-2 marginal cost effectiveness is better than that for the B-1B with the ECM upgrade, even with likely optimistic assumptions about B-1B air defense penetrativity in FY00.

• Cost effectiveness of a strategic force structure with fewer or no B-2s: There have been suggestions that the B-2 program be canceled to save money, that it be delayed or stretched-out, or that it be curtailed after the purchase of fewer aircraft. As demonstrated by Figure 8, the 20-year life-cycle cost effectiveness of a 66 B-2 bomber program is about 75% that of a 132 bomber program. Although we have not developed the data, it is obvious that a stretching-out of the program also would reduce cost effectiveness by making the bombers more expensive. Figures 1, 2, and 10 illustrate the consequences of cancellation of the B-2 program. As previously noted, Force C (with no B-2) has about 1600 fewer weapons than Force B (or A). The consequence is about 1000 fewer effective weapons in the generated case (comparing Force C to Force B) and about 380 fewer effective weapons in the ungenerated case, while the savings is about $84 B. This represents a 15% decline in capability (effective weapons) in the generated case and reduces the number of effective weapons to below 5000 unless silo-based ICBMs execute a PRL (or about 2500 in the ungenerated case). A comparison of Forces B and C (Figure 11) reveals that Force C (with no B-2) has higher cost effectiveness, but not dramatically so. Without PRL of silo-based ICBMs, Force C is actually less cost effective than Force A, which includes B-2s but has a more cost effective Trident force.

• Other factors. While the focus of this paper is on the issue of cost effectiveness, we recognize that there many other factors that must be considered in decisions about the bomber modernization program. One example is the time duration between a decision to launch and weapon delivery for air-carried weapons. Is that a plus (stability) or a minus (lack of capability against time-urgent targets)? A second important issue is roles and missions for penetrating bombers. How valuable are the unique attributes of penetrating bombers as a delivery system (human presence in the target area, conventional payload capability, etc.) as compared to cruise missiles or ballistic missiles?

In summary, the bomber forces are cost competitive with Trident (our basis of comparison) only in the case of generated forces -- the expected alert rate is too low in the ungenerated case for bombers to be a good buy if that scenario is the basis for planning. Even in the generated force case, cost competitiveness would be reduced if alert bombers suffer non-negligible losses from Soviet SLBM attacks during base escape. The B-52H/cruise missile force is more cost effective than the newer bombers unless the B-52Hs suffer disproportionately higher losses from SLBM attacks of escaping alert bombers or cruise missile penetrativity estimates are comparatively too high. The relative cost effectiveness of the B-2 and B-1B forces depend on assumptions about the B-2 weapon loading, whether or not ECM upgrades have been made to the B-1B, and the relative defense penetrativity of the two types of aircraft.

Summary and areas for additional work

We have developed in this paper a methodology to compare strategic system cost effectiveness and have applied it to modernization options under consideration. The cost measures considered include life-cycle costs, marginal costs, and forward costs. Our figure of merit is the number of effective weapons per unit cost. Although the forward costs are important for budgetary decisions, forward cost effectiveness is deemed to be a less reliable figure of merit than life-cycle or marginal cost effectiveness.

The Trident system is shown to be comparatively very cost effective (either life-cycle costs or marginal costs) and we use it as a basis of comparison with other strategic systems. The bomber programs are less cost effective unless forces are fully generated, penetrativity of air defenses is high, and losses of alert bombers during base escape are minimal. The life-cycle cost effectiveness for modernized, survivable ICBM systems tends to be lower than that for Trident because the weapons are not deployed in sufficient numbers to efficiently amortize development costs. Modernized ICBM systems have a marginal cost effectiveness that is comparable to that of Trident.

More work needs to be done. Measures in addition to number of effective weapons should be considered to take into account differences in weapon performance and targeting policies and priorities. Other force options should be examined and cost estimates continually need to be updated. Finally, additional effort should be devoted to characterization of future threats in order to explore the needs and opportunities for (and benefits of) strategic system diversity. It is our belief that the central issue in strategic modernization is the trade-off between force diversity -- to hedge against threats and unexpected failures -- and affordability. The cost effectiveness methodology presented here can help illuminate the issues, but it cannot be expected to resolve the difficult choices that must be made in a time of constrained budgets.

Acknowledgement

This work has been partially supported by funds from the Office of the Deputy Under Secretary of Defense (Strategic & Theater Nuclear Forces) provided to the Center for Technical Studies on Security, Energy and Arms Control at Lawrence Livermore National Laboratory. The author wishes to thank Mr. Greg Hulcher for many useful discussions and comments on the paper.

---

[1]Carlucci, Frank C., Department of Defense Annual Report to the Congress (FY90), p. 6.

[2]Warner III, Edward L., and Ochmanek, David A., Next Moves, Council on Foreign Relations (New York, NY 1989), p. 147.

[3]May, Michael M., Bing, George F., and Steinbruner, John D., *International Security*, Summer 1988, Vol. 13, No. 1. p. 90.

[4]*Aviation Week & Space Technology*, May 29, 1989, p. 31.

[5]According to Epstein, Joshua M., The 1988 Defense Budget, The Brookings Institution (Washington, D.C. 1987) about 5700 to 7600 RVs are needed for 90% damage to rail mobile Peacekeeper and SICBM with Southwest basing. We use $P_S \approx 1$ - (attackers)/7000 for our estimates. From the work of Harvey, et. al. (Harvey, John R., Speed, Roger D., Todaro, Anthony, and Schaffer, Allan, *Carry Hard ICBM Basing -- A White Paper (Executive Summary)*, April 6, 1989, Lawrence Livermore National Laboratory), the P_S is about the same for a carryhard system (see Appendix D) with about 500 Minuteman missiles and 4700 shelters. If SICBMs on hard mobile launchers (HMLs) with basing near Minuteman silos are able to generate about half as much area as the case for basing in the U.S. Southwest, P_S as a function of attack size is the value shown in Table II. These P_S estimates are the same for a carryhard system (see Appendix D) with 50 Peacekeeper missiles and 2800 shelters.

[6]Fridling, Barry E., and Harvey, John R., *International Security*, Winter 1988/89, Vol. 13, No. 3, p. 113.

[7]Hildreth, Steven A., Tinajero, Al, and Woolf, Amy, *START: A Current Assessment of U.S. and Soviet Positions*, Congressional Research Service, June 3, 1988, p. 35.

[8]For example, see *Aviation Week & Space Technology*, November 28, 1988, p. 21.

[9]Reference 2 and Slocombe ("Force posture consequences of the START treaty," *Survival*, September/October 1988, Vol. XXX, No. 5, p. 402) use 16 weapons per B-1B. Hildreth, et. al. use the internal carriage capacity of the aircraft (24 weapons).

[10]Brown, Harold (Co-Chairman), Deterring Through the Turn of the Century, The Center for Strategic and International Studies (Washington, D.C. 1989).

[11]Speed, Roger D., *START and Bomber Survivability*, May 1989, Lawrence Livermore National Laboratory UCID-21713.

[12]*Aerospace Daily*, July 12, 1989, p. 45. The information is a summary of an Air Force briefing paper released by Sen. John Warner (Va.).

APPENDIX A: THE USE OF EXCHANGE MODELS TO EVALUATE OTHER MEASURES OF FORCE EFFECTIVENESS

For the analyses presented in this paper, we use effective weapons as a measure of merit. The principle virtue this measure of merit is that it is simple, while reflecting two important aspects of utility in a retaliatory strike: survivability (including alert rate) and ability to reach the target (reliability and defense penetrativity). A limitation with the measure is that it does not reflect the unique capabilities that certain weapon systems have (i.e., the high accuracy, high yield, and promptness of modern ICBMs that make them particularly useful against time-urgent hard targets). More complicated measures of merit that incorporate aspects of the target base and targeting strategy necessitate the use of an exchange model to simulate the effects of a Soviet first strike and U.S. retaliatory capability against the full spectrum of Soviet targets.

If the analyst attempts attempts to use more sophisticated (exchange) models to examine future force options in greater detail, many more judgements are required about both choices of measures of merit and the scenarios to be considered. A few of the more significant issues and complications are highlighted below. Some of these issues and questions apply even to the simple analyses presented in this paper.

- *What are the target base and the targeting requirements to be considered?* To use an exchange model (or any other tool) to measure force effectiveness against targets, one needs to define a target base (including number of targets and their priority, time urgency, and hardness) and targeting requirements (criteria to measure "defeat" of a target and/or a set of targets). Judgements have to made on many issues: Do the targeting requirements (or the target list) differ in comparing the generated and ungenerated force cases? Are the relative values of targets specified so that a single measure of merit can be constructed or are multiple measures of merit necessary? What if a time-urgent target can not be attacked with an ICBM or SLBM but can only be covered with a bomber-delivered weapon or cruise missile? How does one deal with mobile targets in the analysis? How is an inability to meet all targeting requirements reflected in the measure of merit?

- *How does one measure the benefits of hedging capabilities in a strategic force structure?* In the paper, we make the point that a central issue in selecting future forces is the trade-off between cost and force diversity to hedge against unanticipated failures and threats. A measure of merit must be selected that "rewards" force structures that perform well in both the expected scenario and those for which hedges are sought.

- *How does one measure the benefits of a particular system within the context of other forces also in the inventory?* As a matter of practice (and convenience), most systems analyses consider the effectiveness of a weapon system in isolation, without consideration given to other weapon systems that might be deployed. An example issue, discussed in the paper, is ICBM survivability, which depends on the other ICBM systems deployed that the Soviets might attack. Also, a weapon system under study must offer capabilities that both complement (offer something new) and augment (provide a hedge) the capabilities of other systems.

In short, these questions illustrate some of the complications in developing and evaluating measures of merit that reflect the military worth of strategic weapon systems that might be developed and deployed. Our "effective weapons" measure of merit represents a first step although it suffers somewhat from the "apples and oranges comparison" problems. More sophisticated measures and tools to evaluate the measures can be used, but their use raises additional questions and issues.

APPENDIX B: TRIDENT PROGRAM COSTS

The Trident program considered here includes the development and production of Trident submarines and D-5 missiles, the costs of backfitting the first eight submarines to be capable of launching D-5s, and operations and maintenance. Costs are developed for three cases: 20 submarines with 24 launchers (baseline), 20 submarines with 18 launchers, and 16 submarines with 24 launchers. As is the case for the data presented in Appendices C and D, our cost information is not always the most recent "official" numbers -- rather, they have been gathered from a variety of readily accessible sources (some more official and accurate than others). We expect that, in aggregate, they are accurate within the bounds of uncertainty of future program costs.

The focus of subsequent discussion is on the baseline case, but the information presented is sufficient to reconstruct costs for the variants.

The total costs for a 15 Trident submarine construction program are reported[b1] to be \$31.7 B. The DoD Annual Report to the Congress for FY89 indicates that 16 submarines will have been procured by the end of FY89 and that the construction costs are about \$1.4 B per submarine. The cost of the D-5 backfit program is expected[b2] to be about \$5.8 B. Based on these figures, our estimate of the Trident submarine costs are \$37.6 B for the 20-year life-cycle and \$11.4 B for 10-year forward costs.

Cochran, et. al.[b3] report that the projected cost of the D-5 missile program is \$37.6 B. Elsewhere, they also note that the total build is to be 857 and the figure provided in the CBO report on strategic modernization costs[b4] is 844 missiles. From the DoD Annual Report to Congress for FY89 (and prior years), one finds that about 150 D-5 missiles have been procured through FY89 and that the costs are running about \$30 M per D-5. From this data, our estimates are \$37.6 B for the 20-year life-cycle and \$21.0 B for forward costs.

In FY82 dollars, the operating costs for 15 submarines is reported[b5] to be \$663 M. With adjustment to FY90 dollars,[b6] the figure is $70 M/submarine-year. These costs are combined with the above data for Trident submarine and D-5 missile costs to give:[b7]

	20-yr life-cycle		10-yr forward
20 Trident	$104.3 B	(3.5)	$42.9 B
20 Trident (18 tubes)	$100.7 B	(3.3)	$39.3 B
16 Trident	$ 90.2 B	(3.5)	$30.2 B

In the above, the numbers in parentheses are the marginal costs for the deployment of one additional submarine. All costs are FY90 dollars.

[b1]Cochran, Thomas B., Arkin, William M., and Hoenig, Milton M., Nuclear Weapons Databook, Volume I, U.S. Nuclear Forces and Capabilities, Ballinger Publishing Company (Cambridge, MA 1984), p. 140.

[b2]Modernizing U.S. Strategic Offensive Forces: Costs, Effects, and Alternatives, Congressional Budget Office (Washington, D.C. 1987), p. 51.

[b3]Cochran, et. al., p. 146.

[b4]Reference b2, p. 49.

[b5]Reference b1, p. 140.

[b6]See Appendix E for the procedure followed to adjust costs to FY90 dollars.

[b7]Because the development and procurement costs are roughly half spent, we have not used adjustment factors to modify the reported cost figures to FY90 dollars -- they are treated as equivalent. For the 18 launcher Trident case, the only savings are presumed to be the procurement of fewer missiles. For the ten-year forward costs, an average deployment time of 7.5 years is used.

APPENDIX C: BOMBER PROGRAM COSTS

The three bomber programs considered are the B-52H armed with cruise missiles, the B-1B as a penetrating bomber, and the B-2 as a penetrating bomber. For the B-1B, variants are considered with and without upgrade of the electronic countermeasures (ECM) system. For the B-2, costs are developed for the case of the planned build (132 aircraft) and half that number. The program costs include the cost of the weapon systems to be carried by the delivery systems. That is, all cruise missile program costs are included with the B-52H costs and the SRAM-2 costs are included with the penetrating bomber programs (nuclear bombs are assumed to be free of DoD costs).

The B-2 program cost is reported[c1] to be originally \$36.6 B (FY81), but cost growth in the program is expected to be 10% to 20%. With the 20% estimate and adjustment of dollars, the cost figure is \$62.0 B (FY90). About \$22 B has been spent, according to at least one source.[c2] In our costing, we use[c3] \$274 M as the roll-away cost.

The B-1B program is priced at \$20.5 B (FY81) or about \$28.9 B (FY90). We presume that essentially all the money has been spent. Prior expenditures on the B-1A program were \$6.5 B (FY81) or about \$9.1 B (FY90).[c4] According to *Aviation Week*,[c5] an additional \$1.4 B is needed to obtain a 25% to 30% improvement in penetrating capability (through ECM upgrades). *Aviation Week* notes[c6] that the Congressional Budget Office claims that \$3.4 B is needed to improve the ECM capability and make other necessary changes to the bomber. We are uncertain whether or not the other changes can be accommodated in the existing budget and use the \$1.4 B as additional costs in our comparison of B-1B with and without ECM upgrades. Reference c3 gives the roll-away cost of a B-1B as \$228 M.

For the B-1B and B-2, armament consists of gravity bombs and (in the future) SRAM-2 missiles. Our presumption for purposes of sizing the SRAM-2 program is that loadings will be about half bombs and half SRAM-2s. For the number of weapons loaded, we use the value ascribed by Warner and Ochmanek:[c7] 16 weapons per B-1B and 12 weapons per B-2. The total number of SRAM-2s required would be about 1600 (assuming production of 132 B-2s). This estimate is roughly consistent with the number of SRAM-As (1140 authorized with a "total number in stockpile . . . probably more," according to Cochran, et. al.[c8]). From recent DOD Reports to Congress (FY89 and FY90), about $600 M has been spent on SRAM-2, with about $400 M remaining to be spent on R&D (plus $600 M for B-1B integration). We assume $2 M per missile for SRAM-2 production, which is consistent with our estimate for ALCM.

The B-52 bomber has had a long history with numerous upgrades so that the total program costs are difficult to determine. For purposes of comparison, we use a value of about $150 M per bomber. According to Reference c3, $125 M to $150 M is the cost for a Boeing 747. In addition, this number represents (roughly) a doubling of program costs in successive bomber programs from B-52 to B-1B to B-2 ($150 to $300 to $600 per aircraft). Future B-52 costs include integration of the Common Strategic Rotary Launcher (CSRL), which, according to the DOD Annual Report to Congress (FY90), runs about $75 M per year (we presume through FY94).

The B-52s are able to carry 20 ALCMs/ACMs for a total of about 2000 cruise missiles for the 96 B-52Hs. From Cochran, et. al.[c9] and the DOD Reports to Congress (FY84 and FY85), the cost of the ALCM program is about $4 B or about $5.6 B (FY90) if adjusted from a FY81 average cost. Reference c9 sets the program size at 1500 ALCMs, and if R&D was about 1/3 of program costs, the price per ALCM is about $2.5 M (FY90). We presume the ACM build will about equal the ALCM build for a total of 3000 (to cover testing and spares). Aviation Week[c10] estimates the ACM program cost to be $7 B and we simply ascribe the unit costs to be 25% higher than those for ALCM. ACM is assumed to be near production,[c11] so it is presumed that 1/3 of the $7 B has been spent.

Our estimate for the operations cost of bombers is based on Cochran, et. al.,[c12] who report $1891 M (FY 82) for (then) 320 bombers, which is about $7.7 M/aircraft-year (FY90). We use this figure for all aircraft.

To determine program costs, two additional assumptions are made: The SRAM-2 costs are apportioned equally between the B-2 program and the B-1B program. To compute the 10-year future costs, the B-2 force is available for an average of four years (six years for the 66 B-2 case). With these data, we find the 20-year life-cycle and 10-year forward costs to be:

	20-yr life-cycle		10-yr forward
96 B-52H with CMs	$42.2 B	(0.42)	$12.4 B
97 B-1B	$55.6 B	(0.40)	$17.3 B
97 B-1B with ECM upgrade	$57.0 B	(0.41)	$18.7 B
132 B-2	$84.4 B	(0.44)	$45.9 B
66 B-2	$55.3 B	(0.44)	$25.9 B

In the above, the numbers in parentheses are the marginal costs for the deployment of one additional bomber. All costs are FY90 dollars.

[c1]*Aviation Week & Space Technology*, November 28, 1988, p. 24.

[c2]Epstein, Joshua M., The 1987 Defense Budget, The Brookings Institution (Washington, D.C. 1986), p. 23. The estimate is $20 B (then-year dollars) through 1989, which we adjust to $22 B (FY90).

[c3]Atwood, Donald J., *New York Times*, July 27, 1989, p. 21.

[c4]Welch, J., *International Security*, Fall 1989, Vol. 14, No. 2, p. 63.

[c5]*Aviation Week & Space Technology*, May 29, 1989, p. 31.

[c6]*Aviation Week & Space Technology*, November 28, 1988, p. 29.

[c7]Warner III, Edward L., and Ochmanek, David A., Next Moves, Council on Foreign Relations (New York, NY 1989), p. 147.

[c8]Cochran, Thomas B., Arkin, William M., and Hoenig, Milton M., Nuclear Weapons Databook, Volume I, U.S. Nuclear Forces and Capabilities, Ballinger Publishing Company (Cambridge, MA 1984), p. 71.

[c9]Reference c8, p. 177.

[c10]*Aviation Week & Space Technology*, February, 6, 1989, p. 24.

[c11]In the March 6, 1989 issue of *Aviation Week & Space Technology* there is a photograph of an ACM captive-carry test on a B-52H, p. 26.

[c12]Reference c8, p. 151.

APPENDIX D: ICBM PROGRAM COSTS

There are a variety of ICBM modernization options that have been discussed,[d1] including silo-based Minuteman and Peacekeepers, rail garrison Peacekeeper, Small ICBM (SICBM) on hard mobile launchers (HMLs) based either near Minuteman silos or in military reservations in the Southwest, and Peacekeeper or Minuteman in a carry-hard multiple protective shelter deployment. For an internally consistent set of costs for these options, our principal reference is Deutch.[d2]

According to Cochran, et. al.,[d3] Minuteman program costs are \$12.8 B through FY79, and about \$0.4 B was spent to complete the initial deployment. Reference d3 also gives \$4.8 M (FY77) for the missile flyaway cost. When adjusted to FY90 dollars (by a factor of 1.75), we estimate program costs to be \$23.1 B, with procurement costs of \$8.2 M per missile. Modernization of Minuteman began in FY86. From the Annual Reports to the Congress, we estimate that about \$750 M (FY90) has been spent, and about \$200 M to \$250 M is planned for FY90 and FY91. We assume that this is a ten-year program with three additional years of funding at \$250 M (\$1.25 B remains to be funded for a total program cost of \$2 B). These data are for 1000 silos.

Reference d3 reports that Minuteman operations cost \$345 M in FY82. We adjust this figure to \$450 K/silo-year (FY90) and use this value to estimate the cost of operating either Minuteman or Peacekeeper silos.

For 50 Peacekeeper missiles in silos, Cochran, et. al.[d4] list the cost (FY82) as \$9.8 B for development, \$8.8 B for procurement (to support 100 missiles deployed), and \$0.9 B for military construction. We guess that perhaps \$1.5 B of the development costs were for basing schemes not pursued and exclude those costs. In FY90 dollars, the Peacekeeper costs adjust to \$12.0 B for development (including construction) and \$11.4 B for procurement (or about \$50 M per missile for a total build of 225[d4]). If only 50 Peacekeepers are deployed, we estimate procurement to be \$8.9 B, and from DoD Annual Reports to the Congress, it appears that about 80 have been procured through FY89.

Rail garrison basing of the first 50 Peacekeeper missiles is reported[d5] to cost $5.4 and Deutch[d2] estimates the 15-year costs to be $9.0 B (FY88 or $9.4 B (FY90) plus missile and sunk costs). From these data we derive a figure for the operating costs: $270 M/year. The future 15-year program costs for deployment of the second 50 Peacekeepers in a rail garrison basing mode is $13.0 B (FY88)[d2] or $13.6 B (FY90).

SICBM deployment costs are also provided by Deutch.[d2] For HML/Southwest basing and 15 years of operation, the cost is $30.0 B (FY88) for 500 missiles. The corresponding figures are $24 B for silo basing,[d2] $27 B for HML/Minuteman area basing,[d6] and $23 B for 250 HML/Southwest with 250 missiles with 2 RVs each.[d2] It follows that operations are about $1.25 M/missile-year.[d7] The amount already invested in the SICBM program is about $3 B.[d8]

Cost estimates have been developed for one additional ICBM basing concept: Carryhard (a multiple protective shelter scheme in which the missiles, encapsulated in very hard containers, are shuffled among a large number of austere shelters). For 50 Carryhard Peacekeeper missiles, Deutch[d2] estimates the 15-year costs to be $21 B (FY88). The number of shelters is unspecified. The estimate by Harvey, et. al.[d9] (which we use) is about $25 B for 50 Peacekeeper missiles and 2800 shelters, roughly the same for 160 Minuteman-IIIs and 3100 shelters, and $38 B for 500 Minuteman-IIIs and 4700 shelters. These are 15-year costs (FY89), not including sunk costs. The corresponding costs for Carryhard SICBM are over $40 B.[d8,d9] We use the HML estimate ($1.25 M/missile-year) for operations. For the Minuteman Carryhard case, the development costs are assumed to include necessary upgrades of the Minuteman missile. Minuteman-III deployment is assumed for the per 100-warhead marginal costs and reference d9 is used to deduce the marginal costs for Carryhard.

Because the Carryhard basing concept is not being pursued at this time, a cost comparison with other systems is not made in the main text. In short, the life-cycle cost effectiveness of the Minuteman variant is comparable to 100 Rail Garrison Peacekeeper (generated) and that for Peacekeeper Carryhard is comparable to 500 SICBM/HML.

With the above data, we find the 20-year life-cycle and 10-year forward costs to be:[d10]

	20-yr life-cycle		10-yr forward
1000 Minuteman	$34.1 B		$ 5.8 B
500 Minuteman	$24.8 B	(0.93)	$ 3.3 B
50 Peacekeeper/silos	$21.1 B	(0.77)	$ 5.0 B
50 Peacekeeper/RG	$31.7 B		$12.0 B
50 silo + 50 RG Peacekeeper	$34.4 B		$14.8 B
100 Peacekeeper/RG	$43.2 B	(2.30)	$18.9 B
500 SICBM/Southwest HML	$37.6 B		$23.4 B
500 SICBM/MM area HML	$34.5 B		$20.3 B
250 2-RV SICBM/HML	$31.3 B		$17.1 B
50 Peacekeeper Carryhard	$46.7 B	(1.07)	$29.4 B
500 Minuteman Carryhard	$55.4 B	(1.68)	$30.6 B

The numbers in parentheses shown for some of the cases are the marginal costs for the deployment of 100 additional warheads. All costs are FY90 dollars.

[d1]Brown, Harold (Co-Chairman), Deterring Through the Turn of the Century, The Center for Strategic and International Studies (Washington, D.C. 1989).

[d2]Deutch, John M., *Science*, June 23, 1989, Vol. 244, p. 1445-1450. In general, we have to make three adjustments to Deutch's cost estimates: they are quoted in FY88 and must be adjusted, they are 15-year costs, and for total program costs prior spending needs to be added.

[d3]Cochran, Thomas B., Arkin, William M., and Hoenig, Milton M., Nuclear Weapons Databook, Volume I, U.S. Nuclear Forces and Capabilities, Ballinger Publishing Company (Cambridge, MA 1984), p. 119.

[d4]Reference d3, p. 122.

[d5]Toth, Robert C., *Los Angeles Times*, , July 25, 1989.

[d6]According to *Aviation Week & Space Technology*, February 6, 1989, the differential between Minuteman area and Southwest basing is $3.0 B.

[d7]To determine the operating costs, we considered the difference between SICBM silo-based costs and HML basing costs and used $1 M as the procurement cost per HML.

[d8]*Defense Week*, February 21, 1989.

[d9]Harvey, John R., Speed, Roger D., Todaro, Anthony, and Schaffer, Allan, *Carry Hard ICBM Basing -- A White Paper (Executive Summary)*, April 6, 1989, Lawrence Livermore National Laboratory.

[d10]Some additional information is needed to generate these values: For 100 RG Peacekeeper, the RDT&E and procurement costs (excluding missiles) is taken to be $9.0 B ($5.4 B for the first 50 including RDT&E (1/3 of total) plus 2/3 of $5.4 B for the second). For 50 RG Peacekeeper, the average is 7 years deployment for the 10-year costs, and the figure is 5 years for 100 RG Peacekeeper. For all SICBM and carryhard options, the average deployment is 2 years.

APPENDIX E: ADJUSTMENT FACTORS

For the cost data used in the paper, the quoted source provides the information in then-year dollars or dollars adjusted to a particular fiscal year. We have adjusted all of the data to FY90 dollars. The multiplicative factors used were derived from the "Financial Summary by Major Program" tables in the DOD Annual Reports to the Congress. Each year these tables are provided in then-year dollars and constant dollars, which allows adjustment factors to be deduced:

Fiscal year	Adjustment factor
FY80	1.56
FY81	1.41
FY82	1.30
FY83	1.25
FY84	1.21
FY85	1.15
FY86	1.11
FY87	1.09
FY88	1.05
FY89	1.02

Conversion for the case of FYxx dollars to FY90 dollars is straightforward. For the case of a program that runs over many years with costs in then-year dollars, we made a crude estimate of the "centroid" FY for the program and made an adjustment from that FY.